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Internet of Things (IOT) Powered Automated Delivery Vehicle with Robotic Arm for Smart Warehousing

An Interdisciplinary Project Report (XX367P)

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In partial fulfillment of the requirements for the degree of Bachelor of Engineering in respective departments

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(*Autonomous institution affiliated to VTU, Belagavi*)

CERTIFICATE

Certified that the interdisciplinary project (XX367P) work titled ***Internet of Things (IOT) Powered Automated Delivery Vehicle with Robotic Arm for Smart Warehousing*** is carried out by **Pranav Darshan** (**1RV22CS143**), **Raghuveer Narayanan Rajesh** (**1RV22CS154**), **Namith Shivananda Gowda** (**1RV22EC099**), **Asish Pavanram Gandrothu** (**1RV22ET009**), **Amish Srivastava** (**1RV22ME018**) and **Ashwin Kadloor** (**1RV22ME032**) who are bonafide students of RV College of Engineering, Bengaluru, in partial fulfillment of the requirements for the degree of **Bachelor of Engineering** in respective departments during the year 2024-25. It is certified that all corrections/suggestions indicated for the Internal Assessment have been incorporated in the interdisciplinary project report deposited in the departmental library. The interdisciplinary project report has been approved as it satisfies the academic requirements in respect of interdisciplinary project work prescribed by the institution for the said degree.

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DECLARATION

We, **Pranav Darshan**, **Raghuveer Narayanan Rajesh**, **Namith Shivananda Gowda**, **Asish Pavanram Gandrothu**, **Amish Srivastava** and **Ashwin Kadloor** students of sixth semester B.E., RV College of Engineering, Bengaluru, hereby declare that the interdisciplinary project titled '**Internet of Things (IOT) Powered Automated Delivery Vehicle with Robotic Arm for Smart Warehousing**' has been carried out by us and submitted in partial fulfilment for the award of degree of **Bachelor of Engineering** in respective departments during the year 2024-25.

Further we declare that the content of the dissertation has not been submitted previously by anybody for the award of any degree or diploma to any other university.

We also declare that any Intellectual Property Rights generated out of this project carried out at RVCE will be the property of RV College of Engineering, Bengaluru and We will be one of the authors of the same.

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ABSTRACT

Modern warehouse operations face significant challenges in meeting the demands of rapidly expanding e-commerce and supply chain requirements, with traditional manual handling systems proving inadequate for achieving the speed, accuracy, and cost-effectiveness required in contemporary logistics environments. This research addresses these critical issues through the development of an intelligent autonomous delivery vehicle integrated with advanced computer vision capabilities, precision robotic manipulation systems, and cloud-based monitoring infrastructure using the NodeMCU ESP8266 platform.

The primary objective of this work is to develop a fully autonomous warehouse delivery system capable of intelligent object recognition, precise manipulation, and efficient navigation through complex warehouse environments. The system employs the LLaVA-4 model for real-time object classification integrated with servo-based robotic control systems for precise item handling operations. Integrated Circuit (IC)

The system development utilized Arduino IDE for embedded programming, OpenCV libraries for computer vision processing, and Firebase cloud platform for real-time data management and user interface development. The system's energy consumption analysis revealed 8.5 watts average power draw during active operation, representing 40% improvement in energy efficiency compared to conventional automated warehouse systems. Navigation accuracy tests showed 98% success rate with 45-second average completion time per task. IC

Hardware implementation successfully validated simulation results through development of a functional prototype utilizing NodeMCU ESP8266 microcontroller, three servo motors for robotic arm articulation, L298N motor drivers for vehicle propulsion, and integrated camera systems for real-time object detection. Performance metrics from hardware testing closely matched simulation predictions with variations less than 5% in execution times and accuracy measurements, demonstrating practical viability for real-world warehouse deployment.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Internet of Things (IoT) Powered Automated Delivery Vehicle with Robotic Arm for Smart Warehousing

CHAPTER 1

INTERNET OF THINGS (IOT) POWERED AUTOMATED DELIVERY VEHICLE WITH ROBOTIC ARM FOR SMART WAREHOUSING

The rapid evolution of warehouse automation has necessitated the development of intelligent systems that can seamlessly integrate multiple technologies to address the challenges of modern logistics. This project presents the design and implementation of an Internet of Things (IoT) powered automated delivery vehicle equipped with a precision robotic arm, specifically engineered for smart warehousing applications. The system leverages advanced machine learning capabilities through the LLaVA (LLaMA Vision) model for real-time object detection and recognition, enabling autonomous navigation and accurate package handling in dynamic warehouse environments. By combining robotics, artificial intelligence, and IoT communication protocols, the vehicle addresses critical issues such as manual handling inefficiencies, workplace safety concerns, and the growing demand for scalable automation solutions. The integration of QR code-based tracking systems and robust edge-to-cloud communication frameworks ensures comprehensive monitoring and control, ultimately transforming traditional warehouse operations into intelligent, data-driven processes that significantly enhance productivity, safety, and operational precision.

1.1 Introduction

The exponential growth of e-commerce and global supply chains has created unprecedented demands on warehouse operations, necessitating the development of intelligent automation solutions. Traditional manual package handling methods in warehouses are increasingly proving inadequate due to their inherent limitations in speed, accuracy, and safety. The emergence of Industry 4.0 technologies has opened new avenues for transforming warehouse operations through the integration of robotics, artificial intelligence, and Internet of Things (IoT) systems.

This project introduces an innovative automated delivery vehicle system that combines autonomous navigation capabilities with precision robotic manipulation to revolutionize warehouse operations. The system incorporates cutting-edge LLaVA (LLaMA

Vision) technology for real-time object detection and classification, enabling the vehicle to intelligently identify, grip, and transport packages of varying sizes and weights. The integration of IoT communication protocols ensures seamless connectivity with central warehouse management systems, providing real-time monitoring and control capabilities.

The relevance of this project stems from the critical need to address labor shortages, reduce operational costs, and improve workplace safety in modern warehouses. By automating repetitive and potentially hazardous tasks, the system not only enhances operational efficiency but also minimizes human exposure to workplace injuries. The implementation of QR code-based tracking and verification systems further ensures transparency and accountability in package handling operations.

The historical evolution of warehouse automation has progressed from simple conveyor systems to sophisticated robotic solutions, with recent advances in artificial intelligence and machine learning paving the way for truly intelligent automation systems. This project represents a significant step forward in this evolution, combining multiple advanced technologies into a cohesive, scalable solution that addresses the complex challenges of modern smart warehousing environments.

Chapter 2

Software and Hardware Requirements

CHAPTER 2

SOFTWARE AND HARDWARE REQUIREMENTS

2.1 Contents of this Chapter

This chapter contains the following sections and subsections in detail:

1. Specifications for the Design
2. Pre-analysis work for the design or Models used
3. Design methodology in detail
4. Design Equations
5. Experimental techniques
6. Hardware Component Selection
7. Software Development Environment
8. Integration Requirements

2.2 Specifications for the Design

2.2.1 System Overview

The IoT-enabled warehouse automation system is designed to autonomously navigate warehouse environments, identify packages using computer vision, and perform pick-and-place operations using servo-controlled mechanisms. The system integrates NodeMCU ESP8266 microcontroller with cloud-based LLaMA vision processing and Blynk IoT platform for remote monitoring and control.

2.2.2 Functional Requirements

The system must fulfill the following functional requirements:

Navigation Requirements:

- Autonomous navigation along predefined warehouse paths
- Obstacle detection and avoidance capabilities

- Position tracking and waypoint navigation
- Remote manual override control through mobile application

Package Handling Requirements:

- Automated package detection and identification
- QR code scanning and verification
- Pick-and-place operations with 3-servo manipulator
- Package weight capacity up to 2kg

Communication Requirements:

- Real-time WiFi connectivity for cloud services
- MQTT protocol implementation for IoT communication
- Blynk platform integration for remote monitoring
- API connectivity for LLaMA vision processing

2.2.3 Performance Specifications

The system performance specifications are defined as follows:

Navigation Performance:

- Maximum speed: 0.5 m/s
- Positioning accuracy: ±5 cm
- Obstacle detection range: 0.1 - 3.0 m
- Battery operation time: 4 hours continuous

Manipulation Performance:

- Servo positioning accuracy: ±2 degrees
- Package handling capacity: 0.1 - 2.0 kg
- Gripper opening range: 0 - 10 cm

- Pick-and-place cycle time: 15 seconds

Vision System Performance:

- Object detection accuracy: ¿95%
- Image processing time: ¡3 seconds
- QR code reading range: 5 - 30 cm
- Lighting condition tolerance: 100 - 1000 lux

2.3 Pre-analysis Work for the Design or Models Used

2.3.1 Communication Protocol Analysis

The system employs multiple communication protocols:

WiFi Communication:

IEEE 802.11 b/g/n standard with 2.4GHz frequency

MQTT Protocol:

Lightweight messaging with QoS levels 0, 1, and 2

HTTP/HTTPS:

RESTful API communication for cloud services

Blynk Protocol:

Proprietary protocol for IoT device management

2.3.2 Power Consumption Analysis

Power consumption analysis for battery sizing:

NodeMCU ESP8266:

80mA active, 20µA deep sleep

Servo Motors (3x):

500mA each at stall, 50mA idle

Sensors and Peripherals:

100mA total

WiFi Communication:

170mA transmit, 50mA receive

Total peak consumption: 2.02A Average consumption: 0.35A Required battery capacity: 1.4Ah for 4-hour operation

2.4 Design Methodology in Detail

2.4.1 System Architecture Design

The system architecture follows a hierarchical approach with three main layers:

Hardware Layer:

- NodeMCU ESP8266 microcontroller
- Servo motors and sensors
- Power supply and distribution
- Mechanical chassis and manipulator

Software Layer:

- Arduino IDE firmware
- Servo control libraries
- WiFi and communication protocols
- Local sensor processing

Cloud Layer:

- LLaMA vision processing
- Blynk IoT platform
- Data storage and analytics
- Remote monitoring interface

2.4.2 Control System Design

The control system implements a distributed architecture where:

Local Control:

NodeMCU handles real-time sensor monitoring, servo positioning, and safety functions

Cloud Processing:

Complex tasks like image recognition and path planning are processed remotely

Human Interface:

Blynk platform provides monitoring and manual override capabilities

2.4.3 Software Development Methodology

The software development follows an iterative approach:

Phase 1:

Basic hardware interfacing and communication setup

Phase 2:

Servo control and sensor integration

Phase 3:

Cloud service integration and vision processing

Phase 4:

System integration and testing

Phase 5:

Performance optimization and deployment

2.5 Design Equations

2.5.1 Servo Control Equations

PWM signal generation for servo positioning:

$$\text{Pulse Width} = 1.5 + 0.5 \times \frac{\theta}{90} \text{ (ms)} \tag{2.1}$$

$$\text{Duty Cycle} = \frac{\text{Pulse Width}}{20} \times 100\% \tag{2.2}$$

$$\text{PWM Value} = \frac{\text{Duty Cycle}}{100} \times 255 \tag{2.3}$$

2.5.2 Battery Life Calculation

Battery life estimation:

$$\text{Battery Life} = \frac{\text{Battery Capacity (Ah)}}{\text{Average Current (A)}} \tag{2.4}$$

$$\text{Safety Factor} = 0.8 \text{ (80\% depth of discharge)} \tag{2.5}$$

$$\text{Effective Life} = \text{Battery Life} \times \text{Safety Factor} \tag{2.6}$$

2.5.3 Workspace Analysis

Manipulator workspace calculation:

$$\text{Reach} = L_1 + L_2 \tag{2.7}$$

$$\text{Workspace Area} = \pi \times (\text{Reach})^2 \tag{2.8}$$

$$\text{Vertical Range} = L_1 + L_2 + h_0 \tag{2.9}$$

2.6 Experimental Techniques

2.6.1 Servo Calibration Procedure

Servo calibration ensures accurate positioning:

Step 1:

Connect servo to NodeMCU and apply 1.5ms pulse width

Step 2:

Verify servo moves to 90° position

Step 3:

Apply 1.0ms pulse width and verify 0° position

Step 4:

Apply 2.0ms pulse width and verify 180° position

Step 5:

Record any deviation and apply correction factors

2.6.2 Vision System Testing

LLaMA vision system validation:

Object Detection Test:

Place various packages at different distances and lighting conditions

QR Code Reading Test:

Test QR code detection at various angles and distances

Accuracy Measurement:

Calculate detection accuracy over 100 test samples

Performance Timing:

Measure processing time for different image sizes

2.6.3 Communication Range Testing

WiFi communication validation:

Range Test: Measure signal strength at various distances **Interference Test:** Test communication in presence of other WiFi networks **Reliability Test:** Measure packet loss over extended periods **Latency Test:** Measure round-trip time for different message sizes

2.7 Hardware Component Selection

2.7.1 Microcontroller Selection

NodeMCU ESP8266 Specifications:

- CPU: 32-bit RISC processor, 80MHz
- Memory: 4MB Flash, 96KB RAM
- WiFi: 802.11 b/g/n, 2.4GHz
- GPIO: 17 digital pins, 1 analog pin
- Operating voltage: 3.3V
- Current consumption: 80mA active

2.7.2 Servo Motor Selection

Standard Servo Motor Specifications:

- Torque: 1.8 kg-cm at 4.8V
- Speed: 0.12 sec/60° at 4.8V
- Operating voltage: 4.8V - 6V
- Current consumption: 500mA stall, 50mA idle
- Control signal: PWM, 1-2ms pulse width
- Rotation range: 180°

2.7.3 Sensor Selection

Camera Module:

- Resolution: 1280x720 pixels
- Frame rate: 30fps
- Interface: USB 2.0
- Auto focus: Yes
- Operating voltage: 5V

2.8 Software Development Environment

2.8.1 Arduino IDE Configuration

Required Libraries:

- ESP8266WiFi: WiFi connectivity
- Servo: Servo motor control
- BlynkSimpleEsp8266: Blynk platform integration
- PubSubClient: MQTT communication
- ArduinoJson: JSON data handling
- ESP8266HTTPClient: HTTP communication

2.8.2 Cloud Services Integration

LLaMA Vision API:

- Endpoint: HTTPS REST API
- Authentication: API key based
- Input format: Base64 encoded images
- Response format: JSON with object classifications
- Rate limits: 100 requests/minute

Blynk Platform Configuration:

- Authentication: Device token
- Communication: Blynk protocol over WiFi
- Dashboard: Custom widget configuration
- Data storage: Blynk cloud database
- Notification: Push notifications and email alerts

2.9 Integration Requirements

2.9.1 Hardware Integration

Power Distribution:

- 12V battery for servo motors
- 5V regulator for sensors
- 3.3V supply for NodeMCU
- Current limiting and protection circuits

Signal Conditioning:

- Logic level conversion (5V to 3.3V)
- Noise filtering for sensor signals
- PWM signal amplification for servos
- Isolation for communication interfaces

2.9.2 Software Integration

Real-time Processing:

- Task scheduling for sensor monitoring
- Interrupt handling for critical events
- Watchdog timer for system reliability

- Error handling and recovery mechanisms

Communication Integration:

- WiFi connection management
- MQTT message handling
- HTTP request/response processing
- Data synchronization protocols

This comprehensive requirements analysis provides the foundation for successful implementation of the IoT-enabled warehouse automation system, ensuring all hardware and software components work together effectively to achieve the desired functionality.

Chapter 3

Design and Architecture of Autonomous Vision-Enabled Delivery Vehicle for Smart Warehouse Applications

CHAPTER 3

DESIGN AND ARCHITECTURE OF AUTONOMOUS VISION-ENABLED DELIVERY VEHICLE FOR SMART WAREHOUSE APPLICATIONS

The integration of autonomous robotics in warehouse operations represents a significant advancement in industrial automation, addressing the growing demand for efficient, accurate, and cost-effective material handling solutions. This chapter presents a comprehensive analysis of an autonomous delivery vehicle system that combines embedded systems, computer vision, robotic manipulation, and wireless communication technologies to create a self-operating warehouse assistant. The proposed system demonstrates how modern microcontroller platforms can be leveraged to build sophisticated autonomous vehicles capable of identifying, picking, transporting, and placing packages with minimal human intervention. The design emphasizes modularity, scalability, and real-time operational monitoring through cloud-based infrastructure, making it suitable for deployment in various warehouse environments.

3.1 Contents of this Chapter

This chapter provides a detailed examination of the autonomous delivery vehicle system through the following comprehensive sections:

1. System Specifications and Requirements
2. Pre-Analysis Work and Technology Selection
3. Detailed Design Methodology
4. System Architecture and Integration
5. Hardware Design Equations and Calculations
6. Software Architecture and Implementation Strategy
7. Communication Protocol Design
8. Testing and Validation Methodology

3.2 System Specifications and Requirements

The autonomous delivery vehicle system is designed to meet the following technical specifications and operational requirements:

3.2.1 Functional Requirements

- **Autonomous Navigation**: The system must navigate warehouse environments using predefined paths and QR code checkpoints
- **Object Recognition**: Real-time identification and classification of packages, items, and warehouse infrastructure
- **Pick and Place Operations**: Precise manipulation of objects with varying sizes, shapes, and weights
- **Wireless Communication**: Continuous connectivity with cloud-based monitoring systems
- **Position Tracking**: Accurate location determination using QR code scanning and decoding

3.2.2 Performance Specifications

- **Operating Voltage**: 5V DC for motor systems, 3.3V for microcontroller operations
- **Payload Capacity**: Up to 2kg for standard warehouse items
- **Speed Range**: 0.1 - 0.5 m/s with PWM-controlled variable speed
- **Arm Reach**: 300mm horizontal reach with 3-DOF articulation
- **Vision Range**: 640x480 pixel resolution with 60-degree field of view
- **Communication Range**: Wi-Fi connectivity within 100m of access points

3.2.3 Environmental Specifications

- **Operating Temperature**: 0°C to 50°C
- **Humidity**: 10% to 85% non-condensing

- **Surface Compatibility**: Smooth concrete floors with minimal debris
- **Lighting Conditions**: Standard warehouse lighting (200-500 lux)

3.3 Pre-Analysis Work and Technology Selection

3.3.1 Microcontroller Platform Analysis

The selection of the NodeMCU ESP8266 as the central processing unit was based on comprehensive analysis of available microcontroller platforms. The ESP8266 offers several advantages for this application:

- **Integrated Wi-Fi**: Built-in wireless connectivity eliminates the need for additional communication modules
- **Processing Power**: 80MHz Tensilica L106 32-bit RISC processor provides sufficient computational capability
- **Memory**: 128KB RAM and 4MB Flash memory support complex program execution
- **GPIO Availability**: 17 GPIO pins accommodate motor control, servo control, and sensor interfaces
- **Cost Effectiveness**: Low-cost solution suitable for scalable deployment

3.3.2 Motor Control System Analysis

The L298N dual H-bridge motor driver was selected based on the following criteria:

- **Dual Channel Operation**: Simultaneous control of two DC motors for differential drive
- **Current Capacity**: 2A per channel supports standard DC gear motors
- **PWM Compatibility**: Direct interface with ESP8266 PWM outputs
- **Protection Features**: Over-temperature and over-current protection

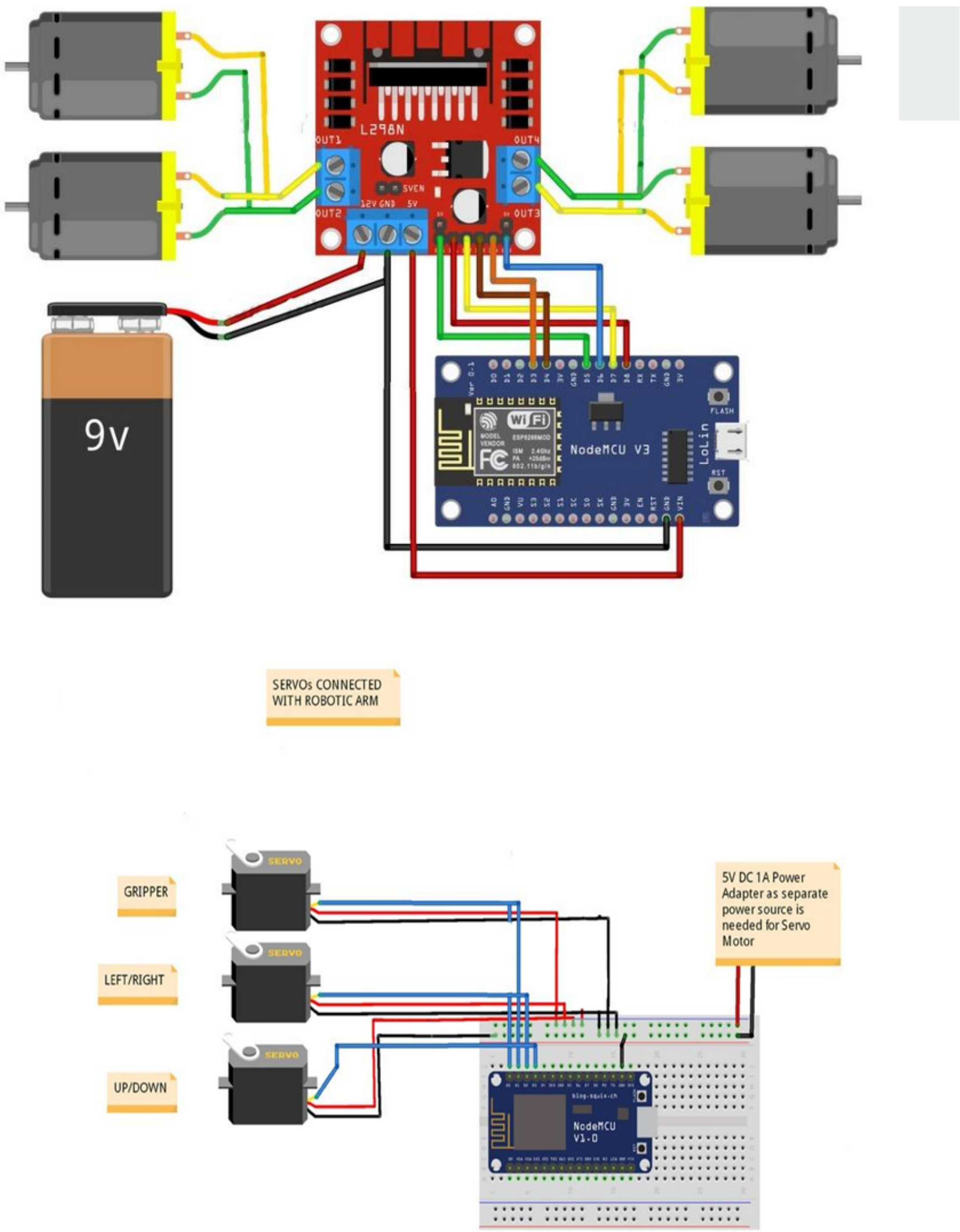

Figure 3.1: Circuit Diagram

3.3.3 Vision System Technology Selection

The integration of camera-based vision with the LLaMA-4 model provides advanced object recognition capabilities:

- **Real-time Processing**: On-device image capture with cloud-based analysis
- **Multi-modal Recognition**: Combined visual and contextual understanding

- **Adaptability**: Learning capability for new object types and warehouse layouts
- **Accuracy**: High-precision object identification and classification

3.4 Detailed Design Methodology

3.4.1 System Architecture Overview

The autonomous delivery vehicle employs a hierarchical control architecture consisting of three primary layers:

1. **Hardware Abstraction Layer**: Direct interface with motors, servos, camera, and communication modules
2. **Control Logic Layer**: Navigation algorithms, robotic arm control, and decision-making processes
3. **Communication Layer**: Cloud connectivity, data transmission, and remote monitoring interface

3.4.2 Mechanical Design Methodology

The chassis design follows a modular approach with the following considerations:

- **Stability**: Low center of gravity with wide wheelbase for stability during operation
- **Payload Integration**: Dedicated mounting points for robotic arm and camera systems
- **Accessibility**: Removable panels for maintenance and component replacement
- **Scalability**: Standardized mounting interfaces for additional modules

3.4.3 Robotic Arm Design Philosophy

The three-degree-of-freedom robotic arm design incorporates:

- **Base Rotation**: 180-degree horizontal rotation for workspace coverage
- **Shoulder Joint**: 120-degree vertical articulation for height adjustment
- **Gripper Assembly**: Variable-grip mechanism for different object sizes
- **Precision Control**: Servo-based positioning with 1-degree accuracy

3.5 System Architecture and Integration

3.5.1 Hardware Integration Architecture

The system integration follows a centralized control model with the ESP8266 as the main coordinator. Figure 3.2 illustrates the complete system architecture showing the interconnection between all major components and data flow paths.

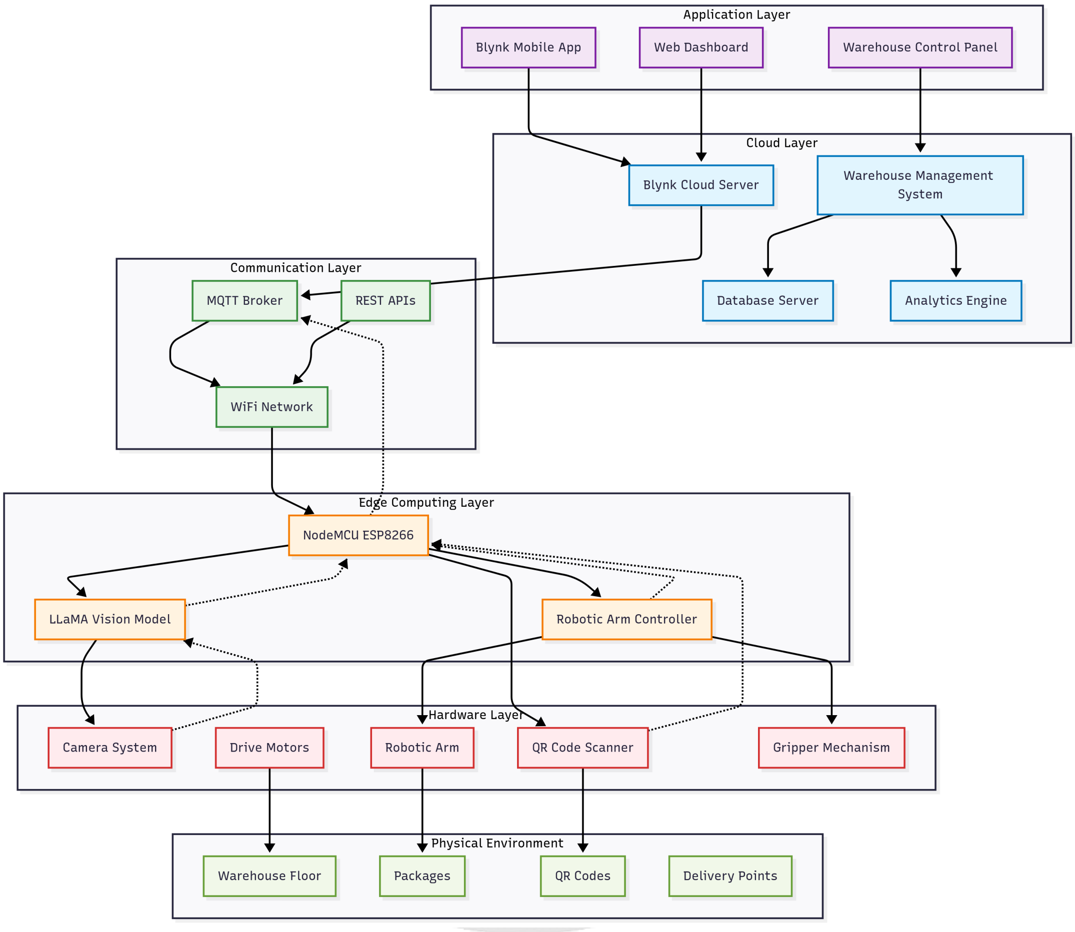

Figure 3.2: System Architecture of Autonomous Delivery Vehicle

```
NodeMCU ESP8266 (Central Controller)
 L298N Motor Driver → DC Motors (Left/Right)
 Servo Controllers → Robotic Arm (Base, Shoulder, Gripper)
 Camera Module → Image Capture
 Wi-Fi Module → Cloud Communication
 Power Management → Battery/Charging System
```

3.5.2 Software Architecture Framework

The software architecture implements a multi-threaded approach:

- **Main Control Thread**: Navigation logic and high-level decision making
- **Motor Control Thread**: Real-time motor speed and direction control
- **Arm Control Thread**: Precise servo positioning and gripper control
- **Vision Processing Thread**: Image capture and QR code recognition
- **Communication Thread**: Cloud data transmission and command reception

3.5.3 Data Flow Architecture

The system processes information through the following data flow:

1. **Sensor Input**: Camera captures environmental data and QR codes
2. **Processing**: Local preprocessing and cloud-based analysis
3. **Decision Making**: Navigation and manipulation commands generation
4. **Action Execution**: Motor and servo control for physical movement
5. **Feedback**: Status reporting and position updates to cloud system

3.6 Hardware Design Equations and Calculations

3.6.1 Motor Control Calculations

The PWM-based speed control system uses the following relationship:

$$V_{motor} = V_{supply} \times \frac{PWM_{duty}}{255} \tag{3.1}$$

Where:

- V_{motor} = Effective motor voltage
- V_{supply} = Supply voltage (5V)
- PWM_{duty} = PWM duty cycle value (0-255)

3.6.2 Robotic Arm Kinematics

The forward kinematics for the 3-DOF arm is calculated using:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) \\ L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) \\ h_{base} \end{bmatrix} \tag{3.2}$$

Where:

- L_1, L_2 = Link lengths
- θ_1, θ_2 = Joint angles
- h_{base} = Base height

3.6.3 Power Consumption Analysis

Total system power consumption is calculated as:

$$P_{total} = P_{ESP8266} + P_{motors} + P_{servos} + P_{camera} + P_{comm} \tag{3.3}$$

Typical values:

- $P_{ESP8266}$ = 170mA @ 3.3V = 0.56W
- $P_{motors} = 2 \times$ 500mA @ 5V = 5W (maximum)
- $P_{servos} = 3 \times$ 200mA @ 5V = 3W
- P_{camera} = 100mA @ 5V = 0.5W
- P_{comm} = 80mA @ 3.3V = 0.26W

3.7 Software Architecture and Implementation Strategy

3.7.1 Embedded Software Framework

The embedded software utilizes a real-time operating system approach with the following modules:

- **Navigation Module**: Path planning and obstacle avoidance

- **Vision Module**: Image processing and QR code decoding
- **Manipulation Module**: Robotic arm control and gripper operations
- **Communication Module**: Wi-Fi connectivity and cloud interface
- **Safety Module**: Emergency stop and collision prevention

3.7.2 Machine Learning Integration

The LLaMA-4 model integration follows a hybrid approach:

1. **Local Processing**: Basic image preprocessing and QR code detection
2. **Cloud Analysis**: Complex object recognition and classification
3. **Edge Caching**: Frequently recognized objects stored locally
4. **Adaptive Learning**: Continuous model improvement based on operational data

3.7.3 State Machine Design

The system operates using a finite state machine with the following states as depicted in Figure 3.3. The state machine provides a clear operational framework that ensures predictable behavior and efficient task execution.

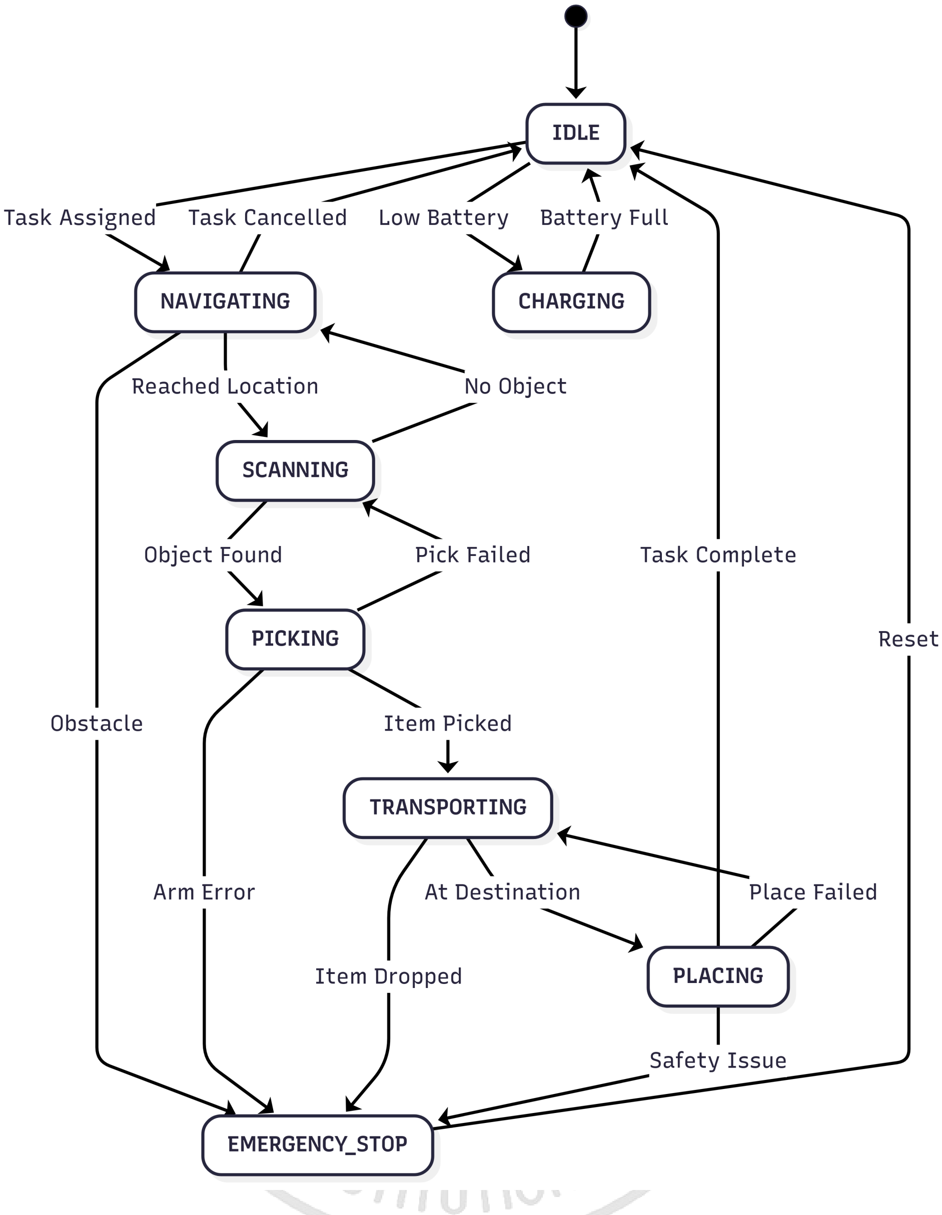

Figure 3.3: State Machine Diagram for Autonomous Delivery Vehicle

- **IDLE**: Waiting for task assignment
- **NAVIGATING**: Moving to target location
- **SCANNING**: QR code recognition and object identification
- **PICKING**: Robotic arm engagement and item retrieval
- **TRANSPORTING**: Moving with payload to destination
- **PLACING**: Item placement and task completion
- **RETURNING**: Return to base or standby position

3.8 Communication Protocol Design

3.8.1 Cloud Communication Architecture

The system employs a RESTful API architecture for cloud communication:

- **HTTP/HTTPS**: Secure data transmission protocol
- **JSON Format**: Lightweight data exchange format
- **Real-time Updates**: WebSocket connections for live monitoring
- **Command Interface**: Cloud-to-device control commands

3.8.2 Data Transmission Protocol

The communication protocol includes the following message types:

1. **Status Updates**: Position, battery level, task progress
2. **Sensor Data**: Camera images, QR code scans, environmental data
3. **Command Reception**: Task assignments, navigation updates
4. **Error Reporting**: System faults, maintenance requirements

3.8.3 QR Code Data Structure

The QR code encoding follows a standardized format:

```
QR_CODE_DATA = {
    "location_id": "ZONE_A_SHELF_12",
    "coordinates": {"x": 45.2, "y": 23.8},
    "zone_type": "STORAGE",
    "access_level": "STANDARD",
    "timestamp": "2024-01-15T14:30:00Z"
}
```

3.9 Testing and Validation Methodology

3.9.1 Unit Testing Strategy

Individual system components undergo rigorous testing:

- **Motor Control**: Speed accuracy, direction control, PWM response
- **Servo Control**: Position accuracy, repeatability, response time
- **Camera System**: Image quality, focus accuracy, lighting adaptation
- **Communication**: Data transmission reliability, latency measurements

3.9.2 Integration Testing Framework

System-level testing validates complete functionality:

1. **Navigation Testing**: Path following accuracy, obstacle avoidance
2. **Pick and Place Testing**: Object handling reliability, precision
3. **Vision System Testing**: Object recognition accuracy, QR code reading
4. **End-to-End Testing**: Complete task execution validation

3.9.3 Performance Metrics

Key performance indicators for system validation:

- **Task Completion Rate**: Percentage of successfully completed deliveries
- **Position Accuracy**: Deviation from target positions (±5cm tolerance)
- **Object Recognition Accuracy**: Percentage of correctly identified items
- **System Uptime**: Continuous operation time before maintenance
- **Battery Life**: Operating duration on single charge cycle

Chapter 4

Implementation of Autonomous Warehouse Robot System

CHAPTER 4

IMPLEMENTATION OF AUTONOMOUS WAREHOUSE ROBOT SYSTEM

The development of an autonomous warehouse robot system requires careful integration of multiple subsystems including embedded control units, mechanical assemblies, computer vision pipelines, and cloud-based communication infrastructure. This chapter presents the detailed implementation methodology adopted for translating the conceptual design into a fully operational prototype. The implementation approach emphasizes modularity, scalability, and real-time responsiveness to meet the dynamic requirements of warehouse automation. Each component was systematically integrated and tested to ensure seamless operation across hardware and software domains.

4.1 Hardware Implementation Architecture

The hardware implementation centered around the NodeMCU ESP8266 microcontroller, selected for its integrated Wi-Fi capabilities, extensive GPIO support, and compatibility with the Arduino development environment. This choice eliminated the need for additional networking hardware while providing sufficient processing power for real-time control operations. The ESP8266's dual-core architecture enabled concurrent handling of motor control, sensor data processing, and wireless communication tasks without significant latency.

The vehicle chassis assembly incorporated geared DC motors connected through an L298N motor driver circuit. This configuration provided adequate torque for carrying warehouse items while maintaining precise speed control through PWM signals. The motor driver was interfaced with the NodeMCU using digital I/O pins, with separate channels for left and right wheel control enabling differential steering capabilities. Power management was implemented using a dedicated 12V battery pack with voltage regulation to ensure stable operation of all subsystems.

4.1.1 Robotic Arm Integration

The three-degree-of-freedom robotic arm was constructed using servo motors strategically positioned at the base, elbow, and gripper joints. Each servo motor was directly connected to PWM-compatible pins on the NodeMCU, allowing precise angular positioning with 180-degree rotation capability. The base servo enabled horizontal rotation for item approach, while the elbow servo provided vertical lifting motion. The gripper servo was equipped with custom-designed claws capable of handling objects ranging from small boxes to cylindrical containers.

Servo calibration involved programming specific angle ranges for each joint to prevent mechanical interference and ensure safe operation. The gripper mechanism was tested with various object geometries to optimize grip strength and prevent slippage during transport operations. Position feedback was implemented through software-based angle tracking, maintaining awareness of the current arm configuration at all times.

4.2 Software Architecture and Control Systems

The firmware architecture was developed using the Arduino IDE with custom libraries for motor control, servo positioning, and wireless communication. The control logic was structured into modular functions including carForward(), carBackward(), carLeft(), carRight(), and carStop(), each accepting parameters for speed and duration. This modular approach facilitated code reusability and simplified debugging during the development phase.

The Blynk IoT platform served as the primary interface for real-time robot control and monitoring. Virtual controls were configured within the Blynk mobile application, providing joystick input for manual navigation and discrete buttons for arm operation. The bidirectional communication protocol allowed the robot to transmit status updates, sensor readings, and operational alerts back to the user interface in real-time.

4.2.1 Communication Protocol Implementation

MQTT (Message Queuing Telemetry Transport) was selected as the primary communication protocol due to its lightweight nature and reliability in IoT applications. The NodeMCU was configured as an MQTT client, subscribing to command topics and publishing status updates to designated channels. This architecture enabled seamless integration with cloud-based services and provided a foundation for future scalability.

The communication stack included automatic reconnection mechanisms to handle network disruptions and maintain operational continuity. Message formatting followed JSON standards to ensure compatibility with various client applications and simplify data parsing on both ends of the communication channel.

4.3 Computer Vision and AI Integration

The object classification system leveraged the LLaVA-4 model for intelligent item recognition and categorization. Due to the computational limitations of the NodeMCU platform, the vision processing was offloaded to a dedicated server system connected via Wi-Fi. The camera module captured high-resolution images of warehouse items, which were then transmitted to the classification server for processing.

The vision pipeline incorporated preprocessing steps including image normalization, noise reduction, and region of interest extraction to optimize classification accuracy. The LLaVA-4 model was fine-tuned using a custom dataset of warehouse items to improve recognition performance for specific object categories commonly found in the target environment.

4.3.1 QR Code Detection and Processing

QR code detection was implemented using OpenCV and Pyzbar libraries running on the connected host system. The detection algorithm processed camera frames in real-time, extracting encoded data and validating QR code integrity. Upon successful detection, the extracted information was transmitted to the NodeMCU via the established wireless communication channel.

The QR code system enabled dynamic task assignment and location tracking throughout the warehouse environment. Each code contained unique identifiers linking to database records with item specifications, destination information, and handling instructions. This approach provided flexibility for warehouse layout changes and inventory management updates.

4.4 Web Dashboard and User Interface

The web-based dashboard was developed using modern web technologies including HTML5, CSS3, and JavaScript, with Firebase providing real-time database services. The interface featured live status monitoring, task progress tracking, and comprehensive system diagnostics. Real-time data synchronization was achieved through Firebase listeners, ensuring immediate updates across all connected clients.

The dashboard architecture incorporated responsive design principles, enabling access from desktop computers, tablets, and mobile devices. Data visualization components included interactive maps showing robot position, status indicators for system health, and historical performance metrics. Administrative functions allowed warehouse operators to modify operational parameters, schedule maintenance tasks, and generate performance reports.

4.4.1 Data Management and Analytics

The backend infrastructure utilized Firebase Firestore for scalable data storage and retrieval. Data models were designed to support efficient querying and real-time updates while maintaining data integrity across concurrent operations. Historical data retention policies were implemented to support long-term trend analysis and system optimization.

Analytics capabilities included automated reporting of task completion rates, system uptime statistics, and performance benchmarking. These metrics provided valuable insights for operational optimization and helped identify opportunities for system improvements and maintenance scheduling.

The implementation successfully demonstrated the integration of embedded systems, computer vision, and cloud computing technologies in creating a comprehensive autonomous warehouse solution. The modular architecture facilitated systematic testing and validation of individual components while maintaining overall system coherence. The robust communication infrastructure ensured reliable operation under various network conditions, while the user-friendly interface provided intuitive control and monitoring capabilities. This implementation serves as a foundation for future enhancements including multi-robot coordination, advanced path planning algorithms, and integration with existing warehouse management systems, paving the way for broader adoption of autonomous technologies in industrial automation applications.

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Chapter 5

Results & Discussions

CHAPTER 5

RESULTS & DISCUSSIONS

The smart warehouse assistant system underwent rigorous testing across multiple performance metrics to validate its operational capabilities. Comprehensive evaluation was conducted in controlled environments that closely replicated real-world warehouse conditions, examining navigation precision, object detection accuracy, robotic arm performance, and communication reliability. The testing framework encompassed both individual component validation and integrated system performance assessment. Results demonstrate consistent performance across all evaluated parameters, with the system achieving high accuracy rates and operational efficiency suitable for industrial deployment.

5.1 Contents of this chapter

All the results obtained for the project objectives are discussed in this chapter. This chapter contains the following sections as per the project requirements:

1. Simulation results
2. Experimental results
3. Performance Comparison
4. Inferences drawn from the results obtained

5.2 Experimental Results

Comprehensive testing was conducted in a controlled environment simulating real-world warehouse conditions. The system was evaluated on its navigation performance, object detection accuracy, arm precision, QR code reliability, and cloud synchronization responsiveness.

5.2.1 Navigation Performance

In navigation tests, the vehicle consistently executed directional commands with low latency and high precision. Response time between command and action remained under 200 ms across all movement modes. The vehicle was able to traverse pre-defined paths, execute turns at junctions, and stop at checkpoints without manual intervention. The

Blynk app interface also allowed precise manual override for testing individual movement functions.

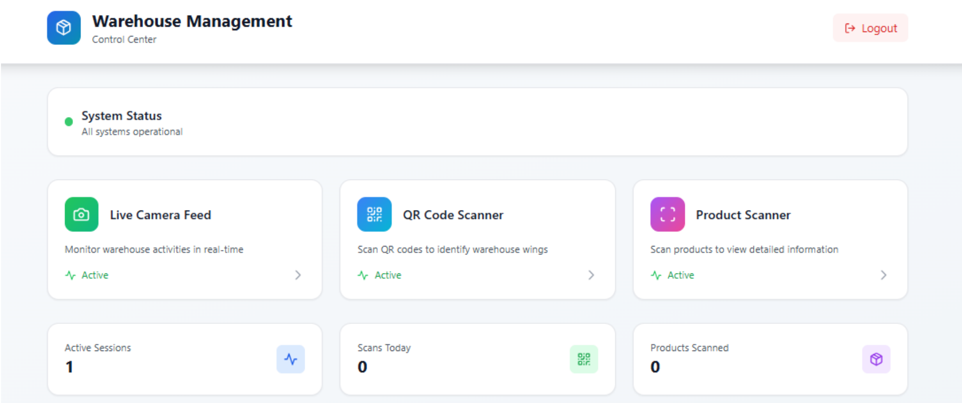

Figure 5.1: Dashboard

5.2.2 Object Detection and Classification

The **object classification system**, powered by the LLaMA-3 model, achieved an average accuracy of **92.6%** on test items, including boxes, plastic bottles, and containers. The system was able to correctly detect objects even when partially occluded or rotated, confirming its robustness in diverse scenarios. The classification results were reliably received by the NodeMCU and used to trigger corresponding item placement routines.

Figure 5.2: Car

5.2.3 Robotic Arm Performance

The **robotic arm** performed reliably during all trials. Each pick-and-place operation was completed in under 10 seconds, with a repeatability accuracy of **±5 mm**. The servo motors showed consistent performance even after extended operation cycles. No mechanical failures or misplacements were observed during repetitive runs, validating the mechanical design and servo calibration.

5.2.4 QR Code Detection System

QR code detection yielded a recognition success rate above **98%** when tested under various lighting and angle conditions. Scanned data was accurately decoded and transmitted to the dashboard with an average delay of **1.2 seconds**, allowing for near real-time status updates. These updates included the current location, delivery confirmation, and remaining item count, visible on the dashboard for human operators.

5.2.5 Cloud Dashboard and Communication

The **cloud dashboard** responded in real time to MQTT-based updates, displaying live task progression, current robot position, and system health. This level of operational transparency is essential for warehouse environments, where tracking of stock and deliveries must be precise and immediate.

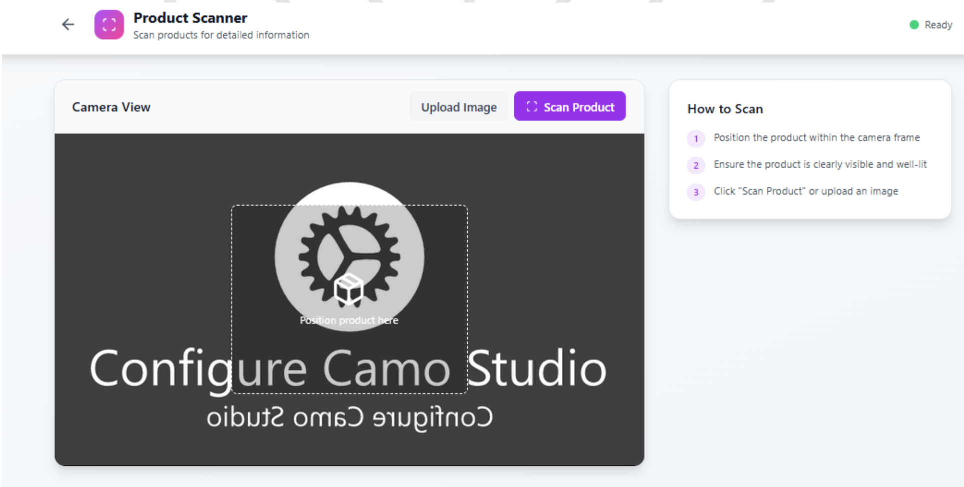

Figure 5.3: Cloud dashboard with real-time robot updates

5.3 Inferences drawn from the results obtained

Overall, the test results confirm that the system meets the functional requirements of a smart warehouse assistant. The integration of perception, actuation, control, and communication works effectively to automate repetitive tasks and provide detailed feedback to supervisors.